13.2 Radioactivity and Nuclear Reactions

SECTION EXPECTATIONS

- Define and describe the concepts and units related to radioactivity.
- Describe the principal forms of nuclear decay.
- Compare the properties of alpha particles, beta particles, and gamma rays in terms of mass, charge, speed, penetrating power, and ionizing ability.
- Compile, organize, and display data or simulations to determine and display the half-lives for radioactive decay of isotopes.

KEY TERMS

- radioactive material
- alpha particle
- beta particle
- gamma ray
- radioactive isotope (radioisotope)
- parent nucleus
- daughter nucleus
- transmutation
- ionizing radiation
- neutrino
- antineutrino
- positron
- half-life
- nuclear fission
- nuclear fusion

Observation of the effects of cathode ray tubes carried out by J.J. Thomson and others stimulated many other scientists to perform related studies in which a material was bombarded with "rays" of various types. When Wilhelm Conrad Röntgen (1845–1923) was using a cathode ray tube, he was surprised to see a fluorescent screen glowing on the far side of the room. Because he did not know the nature of these rays, he called them "X rays." French physicist Henri Becquerel (1852–1908) became curious about the emission of these X rays and wondered if luminescent materials, when exposed to light, might also emit X rays.

At first, Becquerel's experiment seemed to confirm his hypothesis. He wrapped photographic film to shield it from natural light and placed it under phosphorescent uranium salts. When he exposed the phosphorescent salts to sunlight, silhouettes of the crystals appeared when he developed the film. The salts appeared to absorb sunlight and reemit the energy as X rays that then passed through the film's wrapping. However, during a cloudy period, Becquerel stored the uranium salts and wrapped film in a drawer. When he later developed the film, he discovered that it had been exposed while in the drawer. This is the first recorded observation of the effects of radioactivity.

Radioactive Isotopes

Physicists discovered, studied, and used **radioactive materials** (materials that emit high-energy particles and rays) long before they learned the reason for these emissions. As you know, Rutherford discovered **alpha particles** (α) and used them in many of his famous experiments. He examined the nature of alpha particles by passing some through an evacuated glass tube and then performing a spectral analysis of the tube's contents. The trapped alpha particles displayed the characteristic spectrum of helium; alpha particles are simply helium nuclei.

Rutherford also discovered **beta particles**, and other scientists studied their charge-to-mass ratio and showed that beta (β) particles were identical to electrons. French physicist Paul Villard discovered that, in addition to beta particles, radium emitted another form of very penetrating radiation, which was given the name "gamma (γ) rays." **Gamma rays** are a very high-frequency electromagnetic wave. Figure 13.5 shows the separation of these radioactive emissions as they pass between oppositely charged plates.

In Section 13.1, you learned about the nuclei of atoms and about many of the characteristics that made them stable. Did you wonder what would happen to a nucleus if it was not stable? The answer is that it would disintegrate by emitting some form of radiation and transform into a more stable nucleus. Unstable nuclei are called **radioactive isotopes** (or "radioisotopes"). When a nucleus disintegrates or decays, the process obeys several conservation laws — conservation of mass-energy, conservation of momentum, conservation of nucleon number, and conservation of charge. The following subsections summarize the important characteristics of alpha, beta, and gamma radiation.

Alpha Decay

When a radioactive isotope emits an alpha particle, it loses two protons and two neutrons. As a result, the atomic number (Z) decreases by two and the atomic mass number (A) decreases by four. Physicists describe this form of decay as shown below, where P represents the original nucleus or **parent nucleus** and D represents the resulting nucleus or **daughter nucleus**.

$$^{A}_{Z}\mathrm{P} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{A-4}_{Z-2}\mathrm{D}$$

Only very large nuclei emit alpha particles. One such reaction would be the alpha emission from radium-223 ($^{223}_{88}\mathrm{Ra}$). To determine the identity of the daughter nucleus, write as much as you know about the reaction.

$$^{223}_{88}\mathrm{Ra} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{219}_{86}?$$

Then look up the identity of an element with an atomic number of 86, and you will find that it is radon. The final equation becomes

$$^{223}_{88}\mathrm{Ra} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{219}_{86}\mathrm{Rn}$$

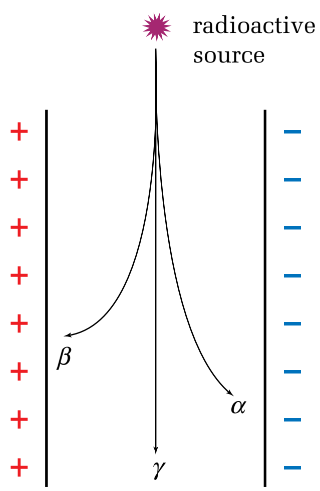

Figure 13.5 Positive alpha particles are attracted to the negative plate, while negatively charged beta particles are attracted to the positive plate. Gamma rays are not attracted to either plate, indicating that they do not carry a charge.

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Pierre and Marie Curie once gave Henri Becquerel a sample of radium that they had prepared. When Becquerel carried the sample in his vest pocket, it burned his skin slightly. This observation triggered interest among physicians and eventually led to the use of radioactivity for medical purposes. Becquerel shared the 1903 Nobel Prize in Physics with the Curies.

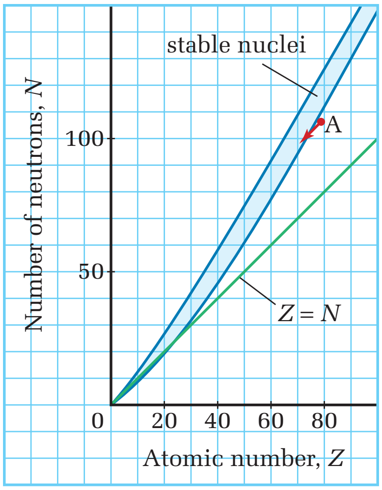

Figure 13.6 The emission of an alpha particle is represented here as a diagonal arrow going down and to the left. This process brings the tip of the arrow to a nucleus that has two fewer neutrons and two fewer protons than the nucleus at the tail of the arrow.

During this reaction, one element is converted into a different element. Such a change is called **transmutation**. Why would such a transmutation result in a more stable nucleus? You can find the answer by studying the simplified representation of stable nuclei in Figure 13.6. The point labelled "A" represents a nuclide that lies outside of the range of stability. The arrow shows the location of the daughter nucleus when the unstable parent loses two neutrons and two protons. As you can see, the daughter nucleus lies within the range of stability. In addition, the helium nucleus — alpha particle — is one of the most stable nuclei of all. Since you now have two nuclei that are more stable than the parent nucleus, the total binding energy increased. The mass defect becomes kinetic energy of the alpha particle and daughter nucleus. Typical alpha particle energies are between 4 MeV and 10 MeV.

Conceptual Problem

- Write the nuclear reaction for the alpha decay of the following nuclei.

(a) ${}^{222}_{86}\text{Rn}$

(b) ${}^{210}_{84}\text{Po}$

(c) ${}^{214}_{83}\text{Bi}$

(d) ${}^{230}_{90}\text{Th}$

Alpha particles do not penetrate materials very well. A thick sheet of paper or about 5 cm of air can stop an alpha particle. In stopping, it severely affects the atoms and molecules that are in its way. With the alpha particle's positive charge, relatively large mass, and very high speed (possibly close to 2×10^7 m/s), it gives some of the electrons in the atoms enough energy to break free, leaving a charged ion behind. For this reason, alpha particles are classified as **ionizing radiation**. These ions can disrupt biological molecules. Because of its low penetrating ability, alpha radiation is not usually harmful, unless the radioactive material is inhaled or ingested.

Beta Decay

When a radioactive isotope emits a beta particle, it appears to lose an electron from within the nucleus. However, electrons as such do not exist in the nucleus — a transformation of a nucleon had to take place to create the electron. In fact, in the process, a neutron becomes a proton, so the total nucleon number (A) remains the same, but the atomic number (Z) increases by one. You can write the general reaction for beta decay as follows, where ${}^{0}_{-1}\text{e}$ represents the beta particle, which is a high-energy electron. The superscript zero does not mean zero mass, because an electron has mass. The zero means that there are no nucleons.

$${}^{A}_{Z}\text{P} \rightarrow {}^{0}_{-1}\text{e} + {}^{A}_{Z+1}\text{D}$$

Many common elements such as carbon have isotopes that are beta emitters.

$$^{14}_{6}\text{C} \rightarrow \, ^{0}_{-1}\text{e} + \, ^{14}_{7}?$$

When you look up the identity of an element with an atomic number of 7, you will find that it is nitrogen. The final equation becomes

$$^{14}_{6}\text{C} \rightarrow \, ^{0}_{-1}\text{e} + \, ^{14}_{7}\text{N}$$

When physicists were doing some of the original research on beta decay, they made some very puzzling observations. Linear momentum of the beta particle and daughter nucleus was not conserved. As well, they determined the spin of each particle and observed that angular momentum was not conserved. To add to the puzzle, the physicists calculated the mass defect and discovered that mass-energy was not conserved.

Some physicists were ready to accept that these subatomic particles did not follow the conservation laws. However, Wolfgang Pauli (1900–1958) proposed an explanation for these apparent violations of the fundamental laws of physics. He proposed the existence of an as yet unknown, undiscovered particle that would account for all of the missing momentum and energy. It was more than 25 years before this elusive particle, the **neutrino** (ν_{e}), was discovered.

In reality, the particle that is emitted with a beta particle is an **antineutrino**, a form of antimatter. The antineutrino has a very small or zero rest mass and so can travel at or near the speed of light. It accounts for all of the "missing pieces" of beta decay. The correct reaction for beta decay should be written as follows. The bar above the symbol ν_{e} for the neutrino indicates that it is an antiparticle.

$$^{A}_{Z}\text{P} \rightarrow \, ^{0}_{-1}\text{e} + \, ^{A}_{Z+1}\text{D} + \overline{\nu_{\text{e}}}$$

Physicists soon discovered a different form of beta decay — the emission of a "positive electron" that is, in fact, an antielectron. It has properties identical to those of electrons, except that it has a positive charge. The more common name for the antielectron is **positron**. Since the parent nucleus loses a positive charge but does not lose any nucleons, the value of A does not change, but Z decreases by one. A proton in the parent nucleus is transformed into a neutron. As you might suspect, the emission of a neutrino accompanies the positron. The reaction for positive electron or positron emission is written as follows.

$$^{A}_{Z}\text{P} \rightarrow \, ^{0}_{+1}\text{e} + \, ^{A}_{Z-1}\text{D} + \nu_{\text{e}}$$

You can understand why beta emission produces a more stable nucleus by examining Figure 13.7. The emission of an electron changes a neutron to a proton; in the chart, this is represented by an arrow going diagonally down to the right. Emission of a positron changes a proton into a neutron and the arrow in the chart goes diagonally upward and to the left.

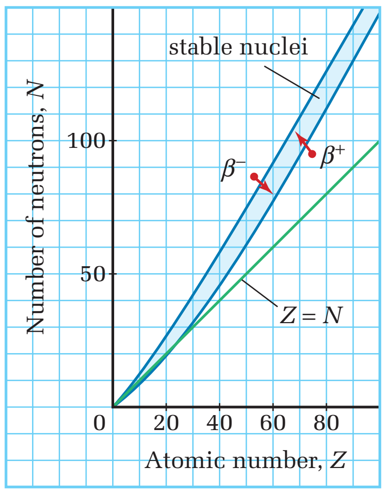

Figure 13.7 If a nucleus lies above the range of stability, it can transform into a more stable nucleus by beta emission. If it lies below the range of stability, it can transform into a more stable ion by emitting a positron. (Arrows are not drawn to scale.)

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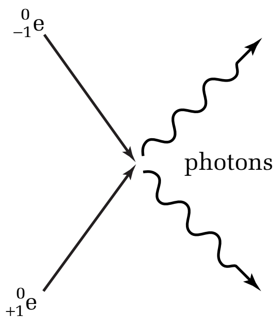
The positron is the antimatter particle for the electron. When they meet, they annihilate each other and release their mass-energy as a gamma photon.

$$^{0}_{1}e + ^{0}_{-1}e \rightarrow \gamma$$



The collision of a particle with its own antimatter particle results in the annihilation of the particles and the creation of two gamma ray photons.

Beta particles penetrate matter to a far greater extent than do alpha particles, mainly due to their much smaller mass, size, and charge. They can penetrate about 0.1 mm of lead or about 10 m of air. Although they can penetrate better than alpha particles, they are only about 5% to 10% as biologically destructive. Like alpha particles, they do their damage by ionizing atoms and molecules, and so are classified as ionizing radiation.

Conceptual Problems

- Free neutrons $\left(^{1}_{0}n\right)$ decay by beta minus emission. Write the reaction.
- Free protons $\left(^{1}_{1}p\right)$ can decay by beta plus emission. Write the reaction.
- Tritium, the isotope of hydrogen that consists of a proton and two neutrons, decays by beta minus emission. Write the reaction.
- Carbon-10 decays by positron emission. Write the reaction.
- Calcium-39 $\left(^{39}_{20}Ca\right)$ decays into potassium-39 $\left(^{39}_{19}K\right)$. Write the equation and identify the emitted particle.
- Plutonium-240 $\left(^{240}_{94}Pu\right)$ decays into uranium-236 $\left(^{236}_{92}U\right)$. Write the equation and identify the emitted particle.
- Lead-109 $\left(^{109}_{46}Pb\right)$ decays into silver-109 $\left(^{109}_{47}Ag\right)$. Write the equation and identify the emitted particle.
- Write the equation for the alpha decay of fermium-252 $\left(^{252}_{100}Fm\right)$.
- Write the equation for the beta positive decay of vanadium-48 $\left(^{48}_{23}V\right)$.
- Write the equation for the beta negative decay of gold-198 $\left(^{198}_{79}Au\right)$.

Gamma Decay

When a nucleus decays by alpha or beta emission, the daughter nucleus is often left in an excited state. The nucleus then emits a gamma ray to drop down to its ground state. This process can be compared to an electron in an atom that is in a high-energy level. When it drops to its ground state, it emits a photon. However, a gamma ray photon has much more energy than a photon emitted by an atom. The decay process can be expressed as follows, where the star indicates that the nucleus is in an excited state.

$$^{A}_{Z}P^{*} \rightarrow ^{A}_{Z}P + ^{0}_{0}\gamma$$

The following is an example of gamma decay:

$$^{192}_{77}Ir^{*} \rightarrow ^{192}_{77}Ir + ^{0}_{0}\gamma.$$

Gamma radiation is the most penetrating of all. It can pass through about 10 cm of lead or about 2 km of air. The penetrating ability of gamma radiation is due to two factors. First, it carries no

electric charge and therefore does not tend to disrupt electrons as it passes by. Second, its photon energy is far beyond any electron energy level in the atoms. Consequently, it cannot be absorbed through electron jumps between energy levels.

However, when gamma radiation is absorbed, it frees an electron from an atom, leaving behind a positive ion and producing an electron with the same range of kinetic energy as a beta particle — often called "secondary electron emission." For this reason, gamma radiation is found to be just as biologically damaging as beta radiation. As in the case of alpha and beta radiation, gamma is classified as ionizing radiation.

Decay Series

When a large nucleus decays by the emission of an alpha or beta particle, the daughter nucleus is more stable than the parent is; however, the daughter nucleus might still be unstable. Consequently, a nucleus can tumble through numerous transmutations before it reaches stability. Figure 13.8 shows one such decay sequence for uranium-238. Notice that the end product is lead-82, then go back to Figure 13.4 on page 550. You will find lead at the peak of the curve of binding energy per nucleon. Lead is one of the most stable nuclei of all of the elements.

Notice that during the progress of the transmutations the following occurs.

- An alpha decay decreases the atomic number by 2 and decreases the atomic mass number by 4.
- A beta negative decay increases the atomic number by 1, while leaving the atomic mass number unchanged.

Knowledge of decay sequences such as the one in Figure 13.8 gives scientists information about the history of materials that contain lead. For example, if a rock contains traces of lead-82, that isotope of lead probably came from the decay of uranium-238 that was trapped in crystals as molten rock solidified in the past. A geologist can determine the original amount of uranium-238 in the rock and compare it to the amount of uranium-238 that remains. Knowing the disintegration rate of the isotopes in the series, a geologist can determine the age of the rock. This method was used to determine that the Canadian Shield contains some of the most ancient rock in the world, aged close to 4 billion years.

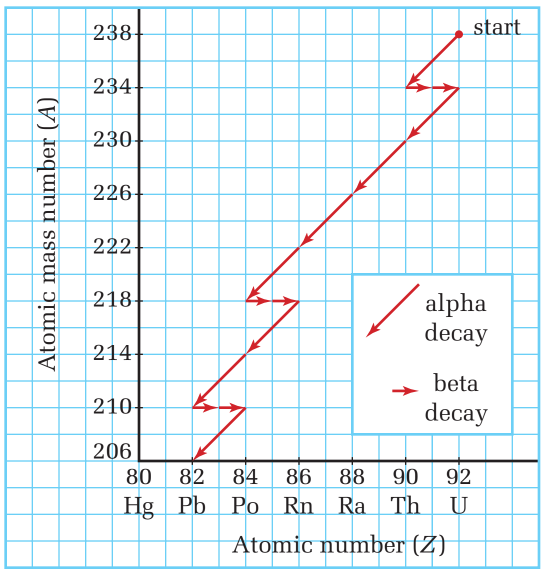


Figure 13.8 This series represents only one of several possible pathways of decay for uranium-238.

Rate of Radioactive Decay

You cannot predict exactly when a specific nucleus will disintegrate. You can only state the probability that it will disintegrate within a given time interval. Using probabilities might seem to be very imprecise, but if you have an exceedingly large number of atoms of the same isotope, you can state very precisely when half of them will have disintegrated. Physicists use the term **half-life**, symbolized by $T_{\frac{1}{2}}$, to describe the decay rate of radioactive isotopes. One half-life is the time during which the nucleus has a 50% probability of decaying. The half-life is also the time interval over which half of the nuclei in a large sample will disintegrate.

Imagine that you had a sample of polonium-218 $\left({}^{218}_{84}Po\right)$. It decays by alpha emission with a half-life of 3.0 min. If you started with 160.0 μg of the pure substance, it would decay as shown in Table 13.3.

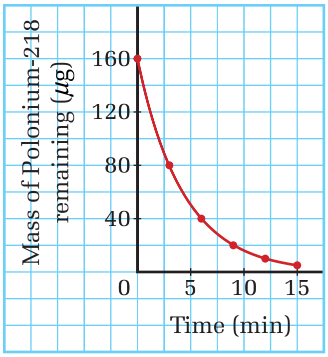


Figure 13.9 A graph of the decay of polonium and all other radioactive isotopes is an exponential curve.

Table 13.3 Decay of Polonium-218

Time (min)	Mass of Po-218 remaining (μg)
0	160.0
3.0	80.0
6.0	40.0
9.0	20.0
12.0	10.0
15.0	5.0

From Figure 13.9 we can estimate the following.

- After 7.0 min, there should be about 32 μg of polonium-218 remaining.
- It would take about 13 min to reduce the mass of polonium-218 to 8.0 μg.

You can obtain more accurate values by using a mathematical equation that relates the mass of the isotope and time interval. You can derive such an equation as follows.

- Let N represent the amount of the original sample remaining after any given time interval.
- Let N_o represent the original amount in the sample; must be given in the same units as N.
- Let Δt represent the time interval, and $T_{\frac{1}{2}}$ represent the half-life.
- After 1 half-life, $N = \frac{1}{2}N_o$.
- After 2 half-lives, $N = \frac{1}{2}\left(\frac{1}{2}N_o\right) = \left(\frac{1}{2}\right)^2 N_o$.

ELECTRONIC LEARNING PARTNER

To enhance your understanding of radioactive decay and half-life, go to your Electronic Learning Partner.

- After 3 half-lives, $N = \frac{1}{2}\left(\frac{1}{2}\right)^2 N_o = \left(\frac{1}{2}\right)^3 N_o$.
- After 4 half-lives, $N = \frac{1}{2}\left(\frac{1}{2}\right)^3 N_o = \left(\frac{1}{2}\right)^4 N_o$.
- You can now see a pattern emerging and can state the general expression in which "n" is the number of half-lives. $$N = \left(\frac{1}{2}\right)^n N_o$$
- However, the number, n, of half-lives is equal to the time interval divided by the time for 1 half-life. $$n = \frac{\Delta t}{T_{\frac{1}{2}}}$$
- Substituting the value for n, you obtain the final equation. $$N = \left(\frac{1}{2}\right)^{\frac{\Delta t}{T_{\frac{1}{2}}}} N_o$$

The amount of sample, N, can be expressed as the number of nuclei, the number of moles of the isotope, the mass in grams, the decay rate, or any measurement that describes an amount of a sample. The unit for decay rate in disintegrations per second is the becquerel, symbolized as Bq in honour of Henri Becquerel.

RADIOACTIVE DECAY

The amount of a sample remaining is one half to the exponent time interval divided by the half-life, all times the amount of the original sample.

$$N = N_o\left(\frac{1}{2}\right)^{\frac{\Delta t}{T_{\frac{1}{2}}}}$$

Quantity	Symbol	SI unit
amount of sample remaining	N	kilograms, moles, or Bq (might also be in number of atoms)
amount in original sample	N_o	kilograms, moles, or Bq (might also be in number of atoms)
elapsed time	Δt	s (often reported in min, days, years, etc.)
half life	$T_{\frac{1}{2}}$	s (often reported in min, days, years, etc.)

Unit Analysis

kilograms = kilograms   kg = kg

Note: The elapsed time and the half-life must be given in the same units so that they will cancel, making the exponent of one half a pure number. Also, the amount of the sample remaining and in the original sample at time zero must be given in the same units.

SAMPLE PROBLEM

Decay of Polonium-218

You have a 160.0 μg sample of polonium-218 that has a half-life of 3.0 min.

(a) How much will remain after 7.0 min?

(b) How long will it take to decrease the mass of the polonium-218 to 8.0 micrograms?

Conceptualize the Problem

- The *half-life* of a radioactive isotope determines the *amount* of a sample at any given *time*.

Identify the Goal

Amount of polonium-218 remaining after 7.0 min

Length of time required for the mass of the sample to decrease to 8.0 μg

Identify the Variables and Constants

Known	Unknown
$m_o = 160.0\ \mu g$	m (at 7.0 min)
$T_{\frac{1}{2}} = 3.0$ min	Δt (at 8.0 μg)
$\Delta t = 7.0$ min	
$m = 8.0\ \mu g$	

PROBLEM TIPS

The data for amounts of a sample, time intervals, and half-lives in decay rate problems can be given in a variety of units. Always be sure that, in your calculations, the amounts of a sample, N and N_o, are in the same units and that the time interval and the half-life are in the same units.

Develop a Strategy

Write the decay relationship

$$N = N_o\left(\frac{1}{2}\right)^{\frac{\Delta t}{T_{\frac{1}{2}}}}$$

Substitute and solve.

$$N = 160.0\ \mu g\left(\frac{1}{2}\right)^{\frac{7.0\ \cancel{min}}{3.0\ \cancel{min}}}$$

$$N = 160.0\ \mu g(0.198\ 425)$$

$$N = 31.748\ \mu g$$

$$N \cong 32\ \mu g$$

(a) The mass remaining after 7.0 min will be 32 μg.

Write the decay equation.

$$N = N_o\left(\frac{1}{2}\right)^{\frac{\Delta t}{T_{\frac{1}{2}}}}$$

Rearrange the equation to solve for the ratio N to N_o.

$$\frac{N}{N_o} = \left(\frac{1}{2}\right)^{\frac{\Delta t}{T_{\frac{1}{2}}}}$$

Substitute numerical values.

$$\left(\frac{1}{2}\right)^{\frac{\Delta t}{3.0\ min}} = \frac{8.0\ \cancel{\mu g}}{160.0\ \cancel{\mu g}}$$

Solve by taking logarithms on both sides.

$$\log\left(\frac{1}{2}\right)^{\frac{\Delta t}{3.0\ \text{min}}} = \log\frac{8.0}{160.0}$$

$$\frac{\Delta t}{3.0\ \text{min}}\log\left(\frac{1}{2}\right) = \log 0.050$$

$$\Delta t = (3.0\ \text{min})\frac{\log 0.050}{\log\left(\frac{1}{2}\right)}$$

$$\Delta t = (3.0\ \text{min})\left(\frac{-1.301\ 003}{-0.301\ 03}\right)$$

$$\Delta t = 12.965\ 78\ \text{min}$$

$$\Delta t \cong 13\ \text{min}$$

(b) The time interval after which only 8.0 μg of polonium-218 will remain is 13 min.

Validate the Solution

These answers are the same as the answers estimated from the graph in Figure 13.9.

PRACTICE PROBLEMS

4. When a sample of lava solidified, it contained 27.4 mg of uranium-238, which has a half-life of 4.5×10^9 a (annum or year). If that lava sample was later found to contain only 18.3 mg of U-238, how many years had passed since the lava solidified?

5. Carbon-14 has a half-life of 5730 a. Every gram of living plant or animal tissue absorbs enough radioactive C-14 to provide an activity of 0.23 Bq. Once the plant or animal dies, no more C-14 is taken in. If ashes from a fire (equivalent to 1 g of tissue) have an activity of 0.15 Bq, how old are they? Assume that all of the radiation comes from the remaining C-14.

6. Radioactive iodine-128, with a half-life of 24.99 min, is sometimes used to treat thyroid problems. If 40.0 mg of I-128 is injected into a patient, how much will remain after 12.0 h?

Nuclear Reactions

When you were solving the problems above, you encountered radioactive isotopes that have half-lives of 3.0 min and 25 min. Did you wonder how any such isotopes could exist and why they had not decayed entirely? Most of the radioactive isotopes that are used in medicine and research are produced artificially. One of the first observations of artificial production of a radioisotope was accomplished by bombarding aluminum-27 with alpha particles as follows.

$${}^{4}_{2}\text{He} + {}^{27}_{13}\text{Al} \rightarrow {}^{31}_{15}\text{P}^{*} \rightarrow {}^{30}_{15}\text{P} + {}^{1}_{0}\text{n}$$

The star on the phosphorus-31 indicates that it is very unstable and decays into phosphorus-30 and a neutron. Phosphorus-30 is a radioisotope that emits a positron. Today, many artificial

isotopes are produced by bombarding stable isotopes with neutrons in nuclear reactors. For example, stable sodium-23 can absorb a neutron and become radioactive sodium-24.

Nuclear Fission

One of the most important reactions that is stimulated by absorbing a neutron is **nuclear fission**, the reaction in which a very large nucleus splits into two large nuclei plus two or more neutrons. The two most common isotopes that can undergo fission are $^{235}_{92}U$ and $^{239}_{94}Pu$. When a nucleus fissions, or splits, a tremendous amount of energy is released in the form of kinetic energy of the fission products — the resulting smaller nuclei. Since the kinetic energy of atoms and molecules is thermal energy, the temperature of the material rises dramatically. You can understand why such large amounts of energy are released by examining the graph of binding energy per nucleon in Figure 13.10.

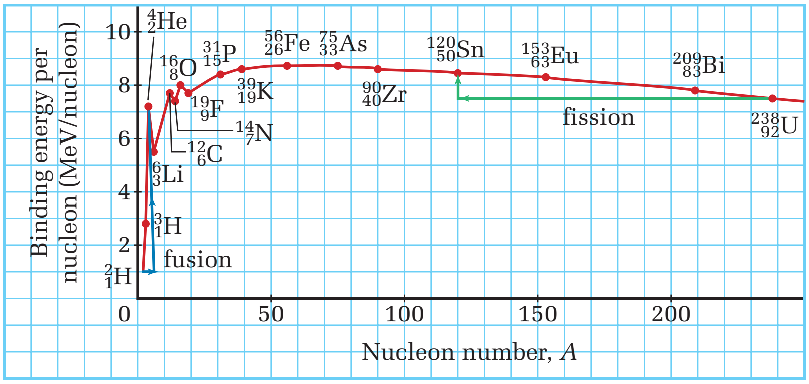


Figure 13.10 The binding energy of mid-range nuclei is greater than that of either very large or very small nuclei.

As you can see in Figure 13.10, when a large nucleus fissions, the smaller nuclei have much larger binding energies than the original nucleus did. Consequently, the sum of the masses of the fission products is much smaller than the mass of the original nucleus. This large mass defect yields the large amount of energy.

Nuclear fission is the reaction that occurs in nuclear reactors. The thermal energy that is released is then used to produce steam to drive electric generators. In this reaction, uranium-235 captures a slow neutron, producing a nucleus of uranium-236. This nucleus is quite unstable and will rapidly split apart. One possible result of this splitting or fission is shown in Figure 13.11. Notice that several neutrons are ejected during the fission. These neutrons can then cause further fissions, causing a chain reaction. However, the neutrons must be slowed down, or the uranium-235 nuclei cannot absorb them. In most Canadian reactors, heavy water is used, since neutrons are slowed down when they collide with the deuterium ($^{2}_{1}H$ or $^{2}_{1}D$) nuclei in the water. The reaction portrayed in

Figure 13.11, ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3{}^{1}_{0}\text{n}$, is only one of a large number of possibilities. Many different fission products are formed.

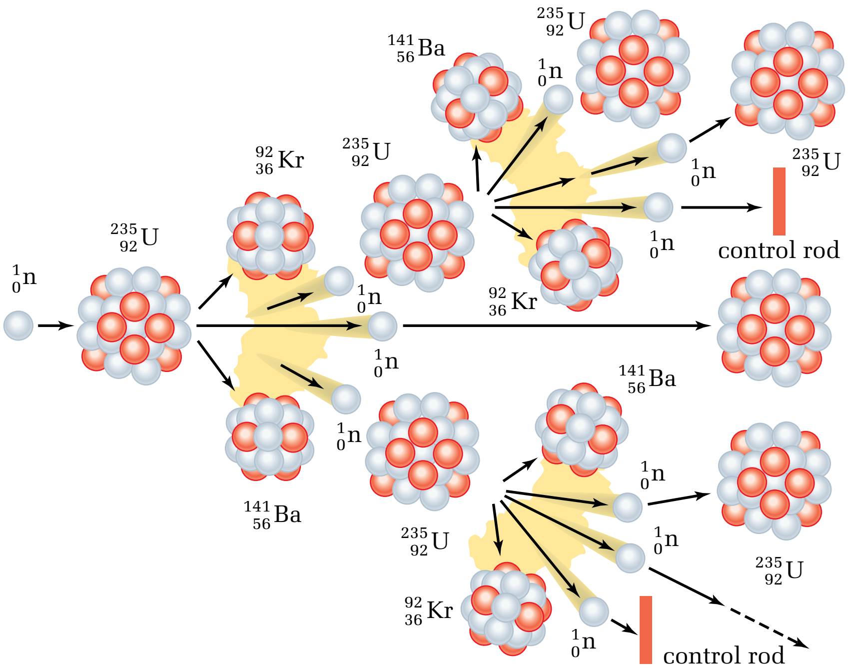


Figure 13.11 The neutrons given off by this nuclear fission reaction must be slowed down before they can be captured by other uranium-235 nuclei and produce further fission.

You have probably heard about the hazards of nuclear energy and the problems with the disposal of the products. Uranium-235 is an alpha emitter with a very long half-life, so it is not a serious danger itself. Alpha radiation is not very penetrating and the long half-life implies a low activity. The fission products cause the hazards. The reason becomes obvious when you examine Figure 13.12, which represents the stable nuclides. Fission products have about the same neutron-to-proton ratio as does the parent uranium nucleus. The fission products therefore lie far outside of the range of stability and so are highly radioactive.

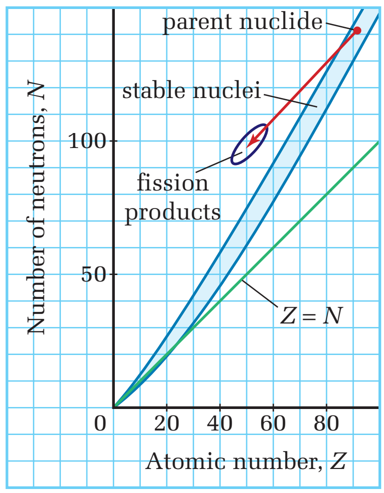


Figure 13.12 Fission products lie above the range of stability and are therefore mostly beta emitters.

Nuclear Fusion

Nuclear fusion is the opposite reaction to nuclear fission. In this process, small nuclei combine together to create larger nuclei. One such fusion reaction involves the combining of two isotopes of hydrogen, deuterium $\left({}^{2}_{1}\text{H}\right)$ and tritium $\left({}^{3}_{1}\text{H}\right)$. During the process, a neutron is released. The equation for the fusion reaction illustration in Figure 13.13 is ${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$.

PHYSICS FILE

Most stars generate energy through a process often called "hydrogen burning." This is not a good term, since no combustion is involved. Instead, single protons or hydrogen nuclei are fused together through a sequence of steps to form helium. Once the amount of hydrogen has diminished to the point where it no longer emits enough radiation to support the outer layers of the star against the inward pull of gravity, the star begins to collapse. This compression of the core causes its temperature to rise to the point at which helium begins to fuse. The star now swells up to become a Red Giant. This process of successive partial collapses and new fusion can continue until the core tries to fuse iron. At this point, the fusion reaction requires energy to continue, rather than releasing energy. The collapse is now catastrophic and the star blazes into a supernova.

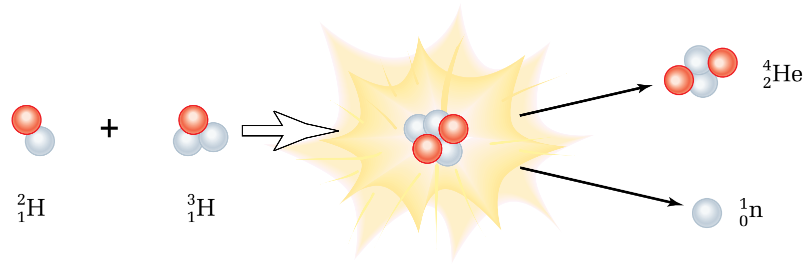


Figure 13.13 The helium nucleus has a much larger binding energy than either deuterium or tritium, so large amounts of energy are released in this nuclear fusion reaction.

Since nuclei repel each other due to their positive charges, they must be travelling at an extremely high speed for them to get close enough for the nuclear force to pull them together. An extremely high temperature can produce such speeds. As long as the product comes before iron in the periodic table, this reaction releases energy (is exothermic). After iron, the reaction requires an input of energy (is endothermic).

Fusion reactions occur in the cores of stars and in hydrogen bombs. Eventually it might be possible to control the fusion reaction so that it can be used to provide reasonably safe energy on Earth for many centuries to come. After all, the oceans contain vast amounts of hydrogen isotopes. Unfortunately, controlled fusion reactions have yet to provide a net output of energy.

SAMPLE PROBLEM

Energy from Nuclear Reactions

Determine the mass defect in the fission reaction given in the text and the amount of energy released due to each fission.

Data

Particle	Nuclear mass (u)
$^{235}_{92}U$	234.993
$^{1}_{0}n$	1.008
$^{141}_{56}Ba$	140.883
$^{92}_{36}Kr$	91.905

Conceptualize the Problem

- *Mass defect* is the *difference* between the total *mass* of the *reactants* and the total *mass* of the *fission products*.
- The *energy* released is the *energy equivalent* of the *mass defect*.

Identify the Goal

The mass defect, Δm, and the energy, E, released during each fission reaction

Identify the Variables and Constants

Known	Implied	Unknown
A, Z and m for all particles	$c = 2.998 \times 10^8 \frac{\text{m}}{\text{s}}$	Δm E

Develop a Strategy

Find the total mass of reactants.

$$m_{\text{neutron}} = 1.008\,665\text{ u}$$
$$m\left({}^{235}_{92}\text{U}\right) = 234.993\text{ u}$$
$$m_{\text{reactants}} = 1.008\,665\text{ u} + 234.993\text{ u}$$
$$m_{\text{reactants}} = 236.002\text{ u}$$
$$m\left({}^{141}_{56}\text{Ba}\right) = 140.883\text{ u}$$
$$m\left({}^{92}_{36}\text{Kr}\right) = 91.905\text{ u}$$
$$m_{3\text{ neutrons}} = 3 \times 1.008\,665\text{ u}$$
$$m_{3\text{ neutrons}} = 3.025\,995\text{ u}$$

Find the total mass of the products.

$$m_{\text{products}} = 140.883\text{ u} + 91.905\text{ u} + 3.026\text{ u}$$
$$m_{\text{products}} = 235.814\text{ u}$$

Find the mass defect by subtraction.

$$\Delta m = 236.002\text{ u} - 235.814\text{ u}$$
$$\Delta m = 0.18767\text{ u}$$

Convert the mass defect into kilograms.

$$\Delta m = (0.18767\text{ u})\left(1.6605 \times 10^{-27}\,\frac{\text{kg}}{\text{u}}\right)$$
$$\Delta m = 3.1163 \times 10^{-28}\text{ kg}$$

Convert the mass into energy, using $\Delta E = \Delta mc^2$.

$$\Delta E = \Delta mc^2$$
$$\Delta E = (3.1163 \times 10^{-28}\text{ kg})\left(2.998 \times 10^8\,\frac{\text{m}}{\text{s}}\right)^2$$
$$\Delta E = 2.8009 \times 10^{-11}\text{ J}$$

The mass defect is 0.1877 u or 3.116×10^{-28} kg. This is equivalent to an energy of 2.801×10^{-11} J.

Validate the Solution

The mass defect is positive, indicating an energy release.

PRACTICE PROBLEMS

7. Another possible fission reaction involving uranium-235 would proceed as follows.

$${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{90}_{38}\text{Sr} + {}^{135}_{54}\text{Xe} + 11\,{}^{1}_{0}\text{n}$$

Determine the mass loss and the amount of energy released in this reaction.

Particle	Mass (u)
${}^{1}_{0}\text{n}$	1.008 665
${}^{235}_{92}\text{U}$	234.993
${}^{90}_{38}\text{Sr}$	89.886
${}^{135}_{54}\text{Xe}$	134.879

continued ▶

continued from previous page

8. Determine the energy that would be released by the fusion of the nuclei of deuterium and tritium as indicated by the equation $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$.

Particle	Mass (u)
$^{2}_{1}H$	2.013 553
$^{3}_{1}H$	3.015 500
$^{4}_{2}He$	4.001 506
$^{1}_{0}n$	1.008 665

9. In the Sun, four hydrogen nuclei are combined into a single helium nucleus by a series of reactions. The overall effect is given by the following equation.

$$4^{1}_{1}H \rightarrow ^{4}_{2}He + 2^{0}_{1}e$$

(a) Calculate the mass defect for the reaction and the energy produced by this fusion.

(b) If 4.00 g of helium contain 6.02×10^{23} nuclei, determine how much energy is released by the production of 1.00 g of helium.

Particle	Mass (u)
$^{1}_{1}H$	1.007 276
$^{4}_{2}He$	4.001 506
$^{0}_{1}e$	0.000 549

Detecting Radiation

Most people have heard of a Geiger counter, which is used to detect ionizing radiation; however, it is only one of a wide variety of instruments used for measuring radiation. Each is designed for a specific purpose, but they all function in the way that alpha, beta, and gamma radiation interacts with matter — by ionizing or exciting atoms or molecules in the object. Some possible interactions, summarized in Figure 13.14, are exposing film, ionizing atoms, or exciting atoms or molecules and causing them to fluoresce or phosphoresce.

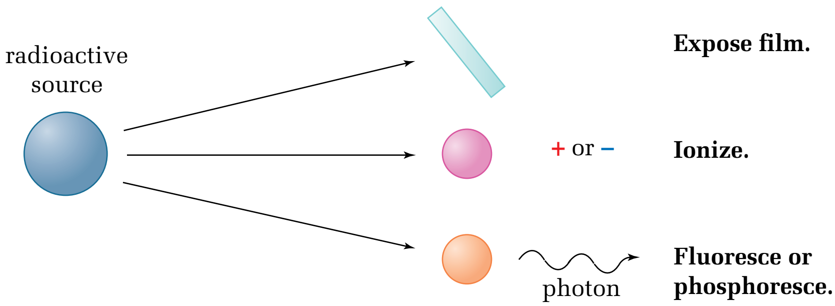


Figure 13.14 Radiation detectors commonly use one of three effects of radiation — the exposing of film, the ionization of matter, or the fluorescence of matter.

Radioactivity was discovered because it darkened film that was wrapped to protect it from light. For many years, people who worked in the nuclear industry or in laboratories where radioisotopes were used wore film badges. Technicians would develop the film, determine the degree of darkening, and calculate the amount of radiation to which the wearer of the badge had been exposed. Currently, many personnel badges contain lithium fluoride, a compound that enters an excited state when it absorbs energy from

radiation. The material is thermoluminescent, meaning that when it becomes excited, it cannot return to the ground state unless it is heated. When heated, it emits light as it returns to its stable state. The technician collects the badges, puts the lithium fluoride in a device that heats it, and reads the amount of light emitted.

Geiger counters and other similar instruments detect the ions created by radiation as it passes through a probe that contains a gas at low pressure. When ionizing radiation passes through the gas, it ionizes some of the atoms in the gas. A high voltage between the wire and the cylinder accelerates the ions, giving them enough kinetic energy to collide with other gas molecules and ionize them. The process continues until an avalanche of electrons arrives at the central wire. The electronic circuitry registers the current pulse.

Geiger counters work well for low levels of radiation, but become saturated by higher levels. Ionization chambers are similar to Geiger counters, but they do not accelerate the ions formed by the radiation. They simply collect the primary ions formed by the radiation, which creates a current in the detector that is proportional to the amount of radiation present in the vicinity of the instrument. One such detector for high levels of radiation is called a "cutie pie."

Figure 13.15 This badge indicates the amount of radiation received by its wearer.

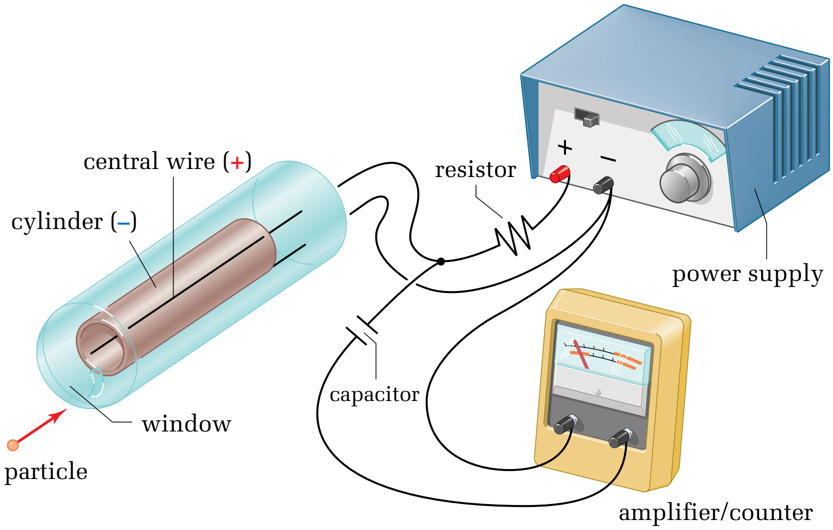


Figure 13.16 The passage of ionizing radiation through this tube creates an avalanche of electrons.

For accurately counting very small amounts of radioactivity, you would probably choose a scintillation counter. A crystal or a liquid consists of a material that, when excited by the absorption of radiation, will emit a pulse of light. Photomultiplier tubes that function on the principle of the photoelectric effect will detect the light and generate an electrical signal that is registered by electronic circuitry.

WEB LINK

www.mcgrawhill.ca/links/physics12

For in-depth information about radiation detection and protection, visit the TRIUMF Internet site. TRIUMF is Canada's national laboratory for particle and nuclear physics, located at the University of British Columbia in Vancouver. Just go to the above Internet site and click on **Web Links**.